

VI. *On the probable Electric Origin of all the Phenomena of Terrestrial Magnetism ; with an illustrative Experiment. By PETER BARLOW, Esq. F.R.S. Cor. Mem. Inst. of France, of the Imperial Academy of St. Petersburg, &c. &c.*

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IN order to show the incompatibility of the observed laws of terrestrial magnetism with the supposition of the earth itself being a magnet, and at the same time their accordance with the laws which appertain to a body whose magnetism is induced by electricity, it will be necessary to take a retrospective view of the several discoveries which have been made, connected with these subjects, since the commencement of the present century, and particularly within the last ten or twelve years. Up to the period of the scientific travels of M. HUMBOLDT, it must be admitted that all the facts with which we were acquainted, relative to terrestrial magnetism, were a mere collection of observations and phenomena, uncertain in themselves, unconnected with each other, and irreducible to any specific laws ; but the confidence inspired by the high character of this distinguished traveller, his accuracy of observation, and the perfection of his instruments, gave a new feature to the inquiry, and laid the foundation of our present knowledge in this science.

M. BIOT was the first to undertake the difficult task of reducing these results to some principle of calculation. Considering the earth as a magnet, he assumed an indeterminate distance to represent the distance of its two poles ; and then, supposing their power to vary inversely as the square of their distance from the point on which they acted, (a law which had been already established,) he obtained a general expression for the direction of a magnetic needle. He then made his indeterminate distance vary ; and comparing at every step his results with those observed, it was found that the nearer the poles were made to approach, the nearer the computed and observed results corresponded ; and finally, that the errors were reduced to a minimum when the two poles were coincident, or indefinitely near to each other.

This is a highly important determination as it relates to the present inquiry; for here we have at once a demonstration that the earth is not a magnet, or at least that it does not act according to the laws of a permanent magnetic body, the distinguishing characteristic of which is, the existence of two poles, distinct and distant from each other; whereas it is shown by this investigation, that in the earth these two poles are indefinitely near to each other and to the earth's centre.

M. BIOR's results, however, in consequence of the generality he had given to his first assumption, were involved in a very intricate formula; but in the mean time a similar task had been undertaken by M. KRAFT, of St. Petersburg, on different principles. This philosopher contented himself with attempting to determine empirically some mathematical formula to connect the different dip observations with each other; and he discovered this very simple relation, viz. "That the tangent of the dip of the needle in any place is equal to double the tangent of the magnetic latitude of that place." M. BIOR, in consequence of this deduction, re-examined his former investigation, and found that his formula after certain reductions, of which he was not before aware it was susceptible, became identical with that of M. KRAFT; and thus the fundamental law of terrestrial magnetism was confirmed by two philosophers acting apart and independently of each other, and on principles entirely different. It followed also from M. BIOR's formulæ, that the intensity of the dipping needle ought to vary inversely as the square root of 4 *minus* 3 times the square of the sine of the dip; and that of the horizontal needle inversely as the square root of 3 *plus* the square of the secant of the dip: conditions which have since been verified, at least approximatively, by observations, extending even to within one or two degrees of the pole itself. And these laws, I beg again to repeat, are entirely inconsistent with those which appertain to a permanent magnetic body, while they will be shown, in what follows, to be the fundamental laws of a body which receives its transient magnetism by induction. We see thus how it happened, that those philosophers of the last century, who endeavoured to illustrate the laws of terrestrial magnetism by what they called *terrellæ*, or round natural magnets, with distinct poles, failed in all their attempts on this subject to establish any mathematical principle of calculation.

It has been seen that up to the year 1809, the phenomena of terrestrial mag-

netism had resisted every prior attempt to reduce them to the power of analysis. It will now be necessary to refer to those which relate to the reciprocal action of iron bodies and a magnetic needle on each other, which were still more uncertain, and apparently more anomalous, than the former.

In 1819 I undertook this investigation, and, after an extensive series of experiments, I succeeded in reducing this reciprocal action likewise to very simple laws, derived empirically from the results I had obtained, but which were obviously only approximative, although the approximation was very close : in the course of these experiments also a very remarkable fact was discovered ; namely, that all the magnetic power of an iron sphere resides on its surface. These first experiments, with the exception of the fact last mentioned, which I had not then discovered, were presented to the Royal Society in 1819. I afterwards extended my first researches, and published the whole in a small tract, entitled, “An Essay on Magnetic Attraction.”

The simplicity of these results, and particularly the circumstance of the magnetic power residing on the surface only of the sphere, led Mr. CHARLES BONNYCASTLE, (at present mathematical professor in the University of Virginia,) to undertake an investigation of the laws which an iron sphere ought to exhibit according to a certain hypothesis relative to induced magnetism ; and he succeeded in eliciting most of the formulæ I had obtained empirically from my experiments. In the second edition of my Essay, I also examined the subject analytically, making a slight alteration in the hypothesis employed by Professor BONNYCASTLE ; and by this means have been enabled to deduce all my experimental laws without exception, and to supply the small corrective part which was obviously wanted in the several formulæ as they were first obtained. Since that time, M. Poisson has employed his powerful analysis to investigate the subject in all its generality ; and I have had the satisfaction of seeing confirmed by so distinguished a mathematician all my original propositions ; and an action considered till that time anomalous, reduced to laws nearly as general and certain as those which govern the planetary motions.

The application of these deductions to the present inquiry is important. It follows from these laws, that if an iron sphere, such as we have supposed in a transient state of magnetic induction, be made to act upon a magnetic needle, isolated from the terrestrial magnetism, it will produce in that needle all the

phenomena which M. HUMBOLDT observed, and which MM. BIOT and KRAFT reduced to determinate laws of action*; the two poles in this case, as in that, being indefinitely near to each other, and to the centre of the sphere. Hence then it follows,

1. That the laws of terrestrial magnetism are inconsistent with those which belong to a permanent magnetic body.

2. That they are perfectly coincident with those which appertain to a body in a transient state of magnetic induction.

These results were incontrovertible; but an insuperable obstacle seemed still to oppose itself to any rational hypothesis relative to the cause of the earth's magnetic power. Up to this period we knew of only one means of inducing magnetism, which was by the approximation of a permanent magnet to a ball or mass of simple iron, and one or two other metals: but what body could be imagined capable of inducing this power in the earth; particularly as the earth preserved its magnetic energy constantly in nearly the same direction, whereas its position with regard to any exterior body was hourly changing? Its magnetism could not therefore be induced by any foreign body; and as no

* The formula indicating the position of a magnetic needle freely suspended from the combined action of the earth and an iron sphere upon it, is

$$\tan \Delta = \frac{3 \cos \phi \cdot \sin \phi}{\frac{d^3}{r^3} \frac{M}{C} + 3 \cos^2 \phi - 1}$$

where Δ is the deflection from the axis of the sphere, ϕ the complement of the magnetic latitude, M the magnetic power of the earth, r the radius of the iron sphere, d the distance of the needle from its centre, and C a constant coefficient dependent on the magnetic power of the iron. In this expression making M vanish according to the above supposition, and substituting $\phi + \delta'$ for Δ , so that δ' becomes the complement of the dip, we have

$$\tan (\phi + \delta') = \frac{3 \cos \phi \sin \phi}{3 \cos^2 \phi - 1}$$

which after an easy reduction becomes

$$2 \tan \delta' = \tan \phi, \quad \text{or} \quad \tan \delta = 2 \tan \lambda$$

where δ is the dip, and λ the magnetic latitude. By a similar process, calling I and I' the intensity of the dipping and horizontal needle, we find

$$I = 2 A \sqrt{\frac{1}{4 - 3 \sin^2 \delta}} \quad \text{and} \quad I' = 2 A \sqrt{\frac{1}{3 + \sec^2 \delta}}$$

which are precisely M. BIOT's formulæ.—See Essay on Magnetic Attractions, page 195.

power in itself could be conceived capable of producing this effect, the deductions above made, although they would have stood incontrovertible, yet the causes of them would have remained inexplicable, but for the important discovery of Mr. OERSTED, which threw a new light upon magnetic investigations.

This philosopher discovered that a wire conducting an electric current was, during the interval of transmission, in a state of magnetic induction. Such a discovery, at such a time, was most fortunate; and not on this point only, but on various others, it excited the attention of all the most distinguished philosophers of Europe. The number of interesting facts which were thus elicited will always form a prominent feature in the scientific history of the nineteenth century, but the greater part of them are unconnected with the present inquiry; I shall therefore only refer to one or two, which have an important bearing upon the question under investigation. As soon as I was informed of this interesting discovery, I was anxious, by experiments as nearly similar, as circumstances would admit, to those I had adopted with the iron ball, to elicit in this case also the laws which govern the reciprocal action of the wire and the needle; and after a pretty long series of experiments I arrived at this conclusion, viz.—

“That the force of each particle in the wire on each particle of the needle varies inversely as the square of the distance, and that the nature of the force is tangential, that is, such as would place a needle, neutralized from the earth’s magnetism, always at right angles to the direction of the wire, and to the direction of the line joining the needle with the centre of action of the wire.” This law, with an account of the experiments from which it was derived, was read to the Royal Society, May 22nd, 1822, and was afterwards published in the second edition of my Essay above referred to.

While I was thus engaged in endeavouring to elicit the law of action between the wire and the needle, M. AMPERE had entered upon a much more extensive investigation; that is, not only of the reciprocal action between the wire and the needle, but also between different wires and galvanic currents on each other. Galvanic needles, both dipping and horizontal, were constructed, which possessed all the properties of the usual magnetic needles. The law of action of galvanic currents on each other was reduced to that of attraction; and by

assuming the magnetism of the needle to be due to an infinite number of galvanic currents parallel to each other and at right angles to the axis, the action of needles on each other, of these on galvanic currents, these currents on each other, and of the earth itself on each, were all reduced to one general principle, admitting of accurate and determinate calculation.

The view which I had taken of the subject was more limited. Having obtained a law which expressed a particular class of these phenomena, I proceeded no further; but it was satisfactory to me to find, that as far as these extended, the expressions were identical, and that all the observed phenomena due to every variety of experiment were equally explicable on the one or the other hypothesis. It will not be necessary to enter further into the many beautiful effects which were obtained by the various arrangements of different galvanic conductors. I shall therefore proceed at once to describe the Experiment alluded to in the head of this article, which is intended, if not to prove, at least to show the high degree of probability, that all terrestrial magnetic phenomena are due only to electricity, and that magnetism, as a distinct quality, has no real existence.

Having, as stated in the preceding part of this paper, discovered that the magnetic power of an iron sphere resides only on its surface; having also shown that when we suppose the earth's magnetism to vanish, the fundamental laws of terrestrial magnetism are exhibited by this superficial action,—the resulting expressions being identical with those obtained by M. Biot for the earth; it occurred to me, by a very natural induction, that if I could distribute over the surface of an artificial globe a series of galvanic currents, in such a way that their tangential power should every where give a corresponding direction to the needle,—such a globe ought to exhibit, while under electrical induction, all the magnetic phenomena of the earth upon a needle freely suspended above it, the needle itself being neutralized from the earth's magnetism, so as to leave it wholly under the influence of this superficial action. This idea was put to the test of experiment as follows.

I procured a wooden globe sixteen inches in diameter, which was made hollow for the purpose of reducing its weight; and while still in the lathe, grooves were cut to represent an equator, and parallels of latitudes at every $4\frac{1}{2}^{\circ}$ each way from the equator to the poles; these grooves were about one

eighth of an inch deep and broad: and lastly, a groove of the same breadth, but of double the depth, was cut like a meridian, from pole to pole, half round. These grooves were for the purpose of laying in the wire, which was effected thus. The middle of a copper wire, nearly ninety feet long and one-tenth of an inch in diameter, was applied to the equatorial groove, so as to meet in the transverse meridian; it was then turned down that groove, one end towards one pole, the other towards the other pole, as far as the first parallel; it was then made to pass round this parallel, returned again along the meridian to the next parallel, then passed round this again, and so on till the wire was thus led in continuation from pole to pole.

The length of wire still remaining at each pole was bound with varnished silk, to prevent contact, and then returned from each pole along the meridian groove to the equator: at this point, each wire being fastened down with small staples, the two wires for the remaining five feet were bound together to near their common extremity, where they opened, to form two points for connecting the poles of a powerful galvanic battery. When this connection was made, the wire became of course an electric conductor, and the whole surface of the globe was put into a state of transient magnetic induction; and consequently, agreeably to the laws of action above described, a neutralized needle freely suspended above such a globe, would arrange itself in a plane passing from pole to pole through the centre, and take different angles of inclination according to its situation between the equator and either pole.

In order to render the experiment more strongly representative of the actual state of the earth, the globe in the state above described was covered by the gores of a common globe, which were laid on so as to bring the poles of this wire arrangement into the situation of the earth's magnetic poles, according to the best observations we have for this determination. I therefore placed them according to the mean results of Sir EDWARD PARRY and Captain FOSTER in latitude 72° N. and 72° S., and on the meridian corresponding with longitude 76° W., by which means the magnetic and true equators cut one another in about 14° E. and 166° W. longitude.

The globe being thus completed*, a delicate needle must be suspended above

* This globe was constructed in 1824, and exhibited by Dr. BIRKBECK, March 26th of that year, at the London Institution.

it, neutralized from the effect of the earth's magnetism, according to the principle I employed in my observations on the daily variation, and described in the Philosophical Transactions for 1823 ; by which means it will become entirely under the superficial galvanic arrangement just described. Conceive now the globe to be placed so as to bring London into the zenith ; then, the two ends of the conducting wire being connected with the poles of a powerful battery*, it will be seen immediately that the needle, which was before indifferent to any direction, will have its north end depressed about 70° , as nearly as the eye can judge, which is the actual dip in London ; it will also be directed towards the magnetic poles of this globe, thereby also showing a variation of about 24° or 25° to W., as is also the case in London. If now we turn the globe about on its support, so as to bring to the zenith places equally distant with England from the magnetic pole, we shall find the dip remains the same ; but the variation will continually change, becoming first zero, and then gradually increasing to the eastward as happens on the earth. If again we turn the globe so as to make the pole approach the zenith, the dip will increase, till at the pole itself the needle will become perfectly vertical. Making now this pole recede, the dip will decrease, till at the equator it vanishes, the needle becoming horizontal. Continuing the motion, and approaching the south pole, the south end of the needle will be found to dip, increasing continually from the equator to the pole, where it becomes again vertical, but reversed as regards its verticality at the north pole.

Nothing can be expected nor desired to represent more exactly on so small a scale all the phenomena of terrestrial magnetism, than does this artificial globe : besides, we know from the mathematical laws of action which have been referred to, that it is not merely an exhibition of effects, but that if we could increase our currents indefinitely, every circumstance of dip and direction would admit of actual and accurate computation.

I may therefore, I trust, be allowed to say, that I have proved the existence of a force competent to produce all the phenomena of terrestrial magnetism, without the aid of any body usually called magnetic, except perhaps it may be

* My battery consisted of twenty zinc and twenty copper plates, ten inches square : but the experiment may be shown satisfactorily by STURGEON'S circular battery with about two feet of copper and one of zinc.

said the small needle employed for exhibiting the effects; and even this, but for its necessary minuteness, might be replaced by a galvanic needle on M. AMPERE's construction. At the same time, I must beg again to observe, that it follows from the laws obtained by M. BIOT, that no position of a single magnet, nor the arrangement of any numbers of such bodies within the globe, could by possibility exhibit the same phenomena, particularly as relates to the intensity of the needle.

I am quite aware that, after all, this does not amount to a demonstration that the magnetic phenomena of the earth are produced only by electricity; yet seeing as we do, in every operation of natural effects with which we are acquainted, that the agents employed are not more numerous than necessary, it will perhaps be admitted that I have at least shown the high probability that all terrestrial magnetic phenomena are due to some particular modification of electricity, and that magnetism, as a distinct quality, has no real existence in nature.

It is true, that as far as the discovery of Mr. OERSTED goes, we have no idea how such a system of currents can have existence on the earth, because, to produce them, we have been obliged to employ a particular arrangement of metals, acids, and conductors; but, fortunately, a subsequent step, not less important than the former, was made by Professor SEEBECK of Berlin, who discovered that the mere application of heat to a circuit composed of two metals, was competent to produce the same development of galvanic and magnetic effects as those above described; and there can be no doubt, that if the conducting wire of the globe I have described, were removed, and each parallel made complete in two metals, that all the phenomena it now exhibits by aid of the galvanic battery might be represented by the application of heat only.

The effect of heat is so obvious in the production of magnetic developments, that I have seen a rectangular circuit on Professor SEEBECK's principle, constructed by MESSRS. WATKINS and HILL, which, by the momentary application of a spirit lamp, became sufficiently magnetic to deflect the needle several degrees, and even the minute change of temperature that could be produced by contact with the hand, exhibited a sensible effect: this circuit, however, was formed of two metals as proposed by Professor SEEBECK; but Mr. STURGEON of

Woolwich has been enabled to produce a similar effect with a rectangle of bismuth only.

This important discovery of M. SEEBECK brings us therefore, as it were, a step nearer to our object, by referring us to the sun as the great agent of all these phenomena ; indeed but one link seems wanted to connect together a chain of highly interesting phenomena, and thereby to reduce to simple and intelligent principles what has hitherto been considered amongst the most mysterious laws of nature.

P.S. I have not in the above article made any reference to the irregularity of the magnetic lines on the earth. I have spoken of the law as deduced by M. BIOT, as if it answered accurately all the conditions required : it is however very well known that there are irregularities which it will not reach, and much credit is due to Professor HANSTEEN for the talent and industry he has applied in the collection of results, and the reduction of them to principles of calculation. These discrepancies however are by no means opposed to the foregoing view of the subject, but are, on the contrary, rather favourable to it ; for if, as is implied in the preceding remark, the development of terrestrial magnetic phenomena be due to the transmission of caloric and inequality of temperature, we ought to expect the same kind of irregularities in this action as we know to exist in the temperature and climate of places situated geographically the same.